A Direct Simulation-Based Study of Radiance in a Dynamic Ocean

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Award Number: N00014-06-1-0027
http://www.mit.edu/~vfrl/

LONG-TERM GOALS

The ultimate goal is to develop direct simulation/physics-based forward and inverse capabilities for radiance prediction in a dynamic ocean environment. This direct simulation-based model will include and integrate all of the relevant dynamical processes in the upper ocean surface boundary layer into a physics-based computational prediction capability for the time-dependent radiative transport.

OBJECTIVES

To include and integrate relevant dynamical processes in the upper ocean surface boundary layer (SBL) into a physics-based computational prediction and inverse capability for the time-dependent radiative transport:

- Develop direct simulation of upper ocean hydrodynamic processes and forward prediction of radiative transfer

- Obtain understanding, modeling and parameterizations of dependencies of oceanic radiance on the surface wave environment

- Provide guidance for field measurements and obtain cross validations and calibrations with direct simulations and modeling

- Provide a framework for inverse modeling and reconstruction of ocean surface and above water features based on sensed underwater radiance data

To reach these objectives, we had and would continue to have a close collaboration with Professor Lian Shen of the Johns Hopkins University (JHU) on the modeling of free surface turbulence roughness.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**
4. TITLE AND SUBTITLE **A Direct Simulation-Based Study of Radiance in a Dynamic Ocean (MIT)**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Massachusetts Institute of Technology,Center for Ocean Engineering,77 Massachusetts Ave,Cambridge,MA,02139**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

A simulation approach, based on direct physics-based simulations and modeling, is applied to solve the problem of ocean radiance transport (RT) in a dynamic ocean SBL environment that includes nonlinear capillary-gravity waves (CGW), free-surface turbulence (FST) roughness, wave breaking, and bubble generation and transport. The radiative transport is governed by Snell's law and Fresnel transmission at the water surface, and absorption and multiple scattering in the water underneath. The complex dynamic processes of the ocean SBL, the nonlinear CGW interactions, the development and transport of FST, and the generation and transport of bubbles are modeled using physics-based computations. The modeling of these hydrodynamic processes is coupled with the computation of radiative transport.

Nonlinear CGW: An efficient phase-resolved computational approach based on Euler equations is used to compute spatial and temporal nonlinear evolution of capillary and gravity waves. This computational tool builds on an efficient high-order spectral method that we developed for direct simulations of nonlinear gravity wavefield evolution. Nonlinear gravity-gravity and gravity-capillary wave interactions are accounted for up to an arbitrary order in the wave steepness. With high computational efficiency, this approach enables phase-resolved simulations of large-scale nonlinear CGW.

FST-Wave Interactions: Navier-Stokes equations based DNS is employed to resolve all eddies in free surface turbulence. LES and LWS are used to compute large eddy and large wave components explicitly, with effects from small-scale motions being represented by subgrid-scale (SGS) models. Fully nonlinear viscous free-surface boundary conditions are imposed. Effects of surfactants are captured through the Plateau-Marangoni-Gibbs effect with surfactant transport directly simulated.

Steep and Breaking Waves: A Navier-Stokes equations solver for fully coupled air-wave interactions with a level-set method for free surface tracking is employed to compute the details of free surface signature and dissipation due to steep and breaking waves.

Bubble Transport in CGW and FST: Direct simulation is developed to compute bubble motion in CGW and FST environment. Both Lagrangian and Eulerian approaches are used to trace bubble trajectories. Bubble motion is subject to forces due to added mass, buoyancy, drag, lift, and fluid stress gradients arising from the continuous-phase acceleration. Bubble source is determined based on experimental measurements and/or existing data.

Radiative Transfer in CGW and FST: Monte Carlo simulation of radiance transfer (RT) (e.g. Walker 1994) is developed with the free surface deformation obtained from direct CGW and FST computations. The effects of absorption and multiple scattering on RT are included. Bubble scattering effects are also considered based on bubble distribution and transport and Mie theory.

WORK COMPLETED

- ***Development of nonlinear CGW simulation capability***: Continued the development of a direct simulation capability for nonlinear CGW evolution by extending the high-order spectral method for gravity waves to general broadband nonlinear wavefield interactions involving swell, seas, and capillary waves. The focus was on the inclusion of capillary waves, long-short wave interactions, wave breaking dissipation, dissipation due to free surface turbulence and energy input by wind.

- ***Development of Monte Carlo RT simulation***: We developed a three-dimensional coupled atmosphere-ocean Monte Carlo radiative transfer simulation capability for both polarized and unpolarized lights. The RT simulation is time independent, but accounts for the effect of complex unsteady three-dimensional ocean surface including CGW and FST roughness. In RT, multiple refractions at ocean surface, total internal reflection, all orders of multiple scattering, and scattering and absorption of both water molecules and marine aerosols are all considered. In order for practical applications, various techniques including the use of biased sampling algorithms and parallelization of the code (with MPI) were employed to speed up the program.

- ***Validation of RT simulations and investigation of underwater irradiance characteristics in CGW and FST environments***: Continued to validate RT simulations by comparisons to available experimental data and other model predictions. We performed the Monte Carlo radiative transfer simulations under various surface wave conditions for understanding the correlation between underwater irradiance and ocean environments.

RESULTS

We systematically validated the developed RT simulation model by making direct comparisons with theories, existing numerical model prediction, and available experimental measurements. The developed RT simulation model is effective and useful for predicting three-dimensional polarized and unpolarized radiative transfer in the atmosphere-ocean system. The RT model was used to investigate the characteristics of underwater irradiance in various ocean surface environments. Of particular interest is the effect of surface wave nonlinearity upon underwater irradiance characterization.

Nonlinear wave effects on underwater radiance distribution: Consideration of nonlinearity of surface waves is of critical importance in the study of underwater irradiance as it affects the profile of ocean-atmosphere interface. To understand the correlation between wave nonlinearity and underwater radiance distribution, we first compared the underwater radiance distribution in an (linear) Airy wave and a (fully nonlinear) Stokes wave. As shown in figure 1, as an example, three receivers are placed directly under wave crest, 90^o phase point, and wave trough. For the three-dimensional Monte Carlo RT simulations, we assume that the radiance from atmosphere is normally incident on ocean surface without diffusion. The optical parameters in coastal water are: $a=0.179\ m^{-1}$ and $b=0.219\ m^{-1}$, and Petzold phase function is used. The wave parameters are: steepness $\varepsilon = 0.4$ and wavelength $\lambda=1.0$m. The computational parameters are: side length of the square domain $L=10\lambda$, 256^2 horizontal grids in the computational domain, number of photons $M=10^7$, and polar angle resolution of 1^o.

Figure 2 shows the comparison of the radiance distribution at optical depth $\zeta=1$ under a linear Airy wave and a fully nonlinear Stokes wave. Apparent significant differences in radiance distribution, especially at small view angles, due to nonlinear wave effects are seen under the crest and 90^o phase point. Interestingly the radiance distribution remains almost unaffected by nonlinear wave effects under the trough of the wave. The spatial frequency spectrum of downwelling irradiance indicates that due to nonlinear wave effects, the irradiance possesses a strong intensity at zero frequency but much suppressed side-lops. Such nonlinear wave effects in underwater radiance distribution become stronger/weaker as the optical depth decreases/increases.

Figure 3 plots the underwater radiance distribution at optical depth $\zeta=1$ for three different wave slopes ($ka = 0.1, 0.25, 0.4$) at the 90^o phase point. It is seen that with the increase of surface wave steepness, the nonlinear effect on underwater radiance distribution becomes more apparent.

Effects of short waves on underwater radiance distribution: Structure of underwater radiance strongly depends on the curvature of ocean surface that is largely affected by the presence of short waves. On ocean surface, the motion of short waves is coupled with long waves. In particular, this coupling is strongly nonlinear. Properly accounting for nonlinear long-short wave interaction effects is of critical importance to understanding and prediction of underwater radiance distribution and characterization. Figure 4 compares two-dimensional downwelling irradiance patterns under linear and nonlinear wavefields in the presence of long and short waves. The wavefield is composed of one primary long wave and one primary short wave with a wavelength ratio of 10. The steepnesses of short and long waves are identical. It is seen that in the presence of long and short waves, the underwater irradiance pattern varies significantly with the inclusion of nonlinear effects in long-short wave interactions.

IMPACT/APPLICATIONS

The capability of accurate prediction of the irradiance transfer across ocean surface and in the water may enable the development of a novel approach for accurate measurements of complex ocean boundary layer processes and reliable detection of the presence of structures/objects on or above ocean surface based on sensed underwater irradiance data.

PUBLICATIONS

1. Z. Xu & Yue, D. K.P. “Influence of nonlinearity of ocean surface waves on the spatial and temporal fluctuations of underwater light fields”, Ocean Science Meeting, Orlando, FA, March, 2008.

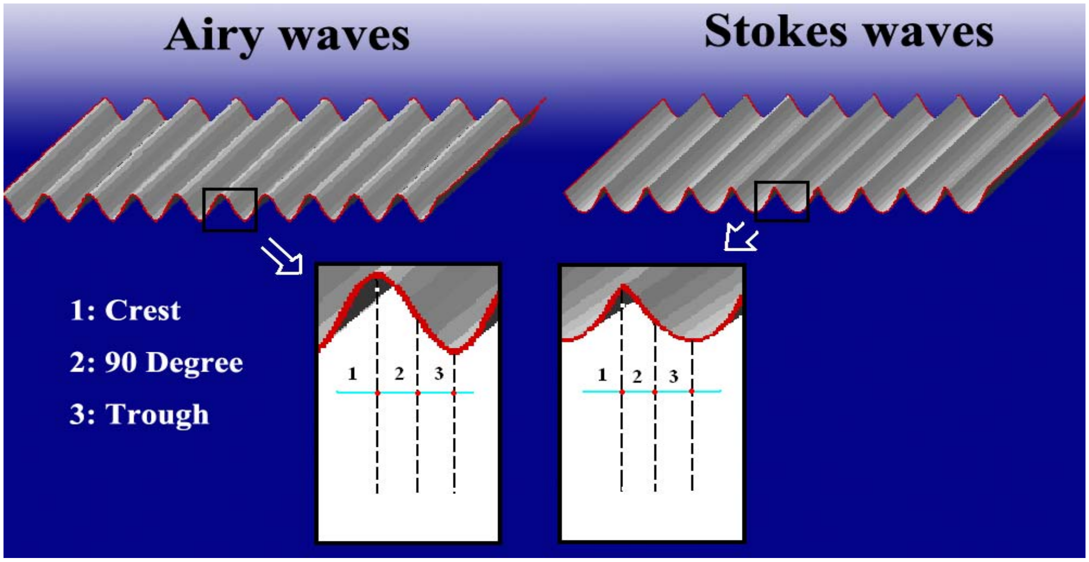


Figure 1. Sketch of three receivers under an (linear) Airy wave and a (fully nonlinear) Stokes wave for the study of underwater radiance characterization.

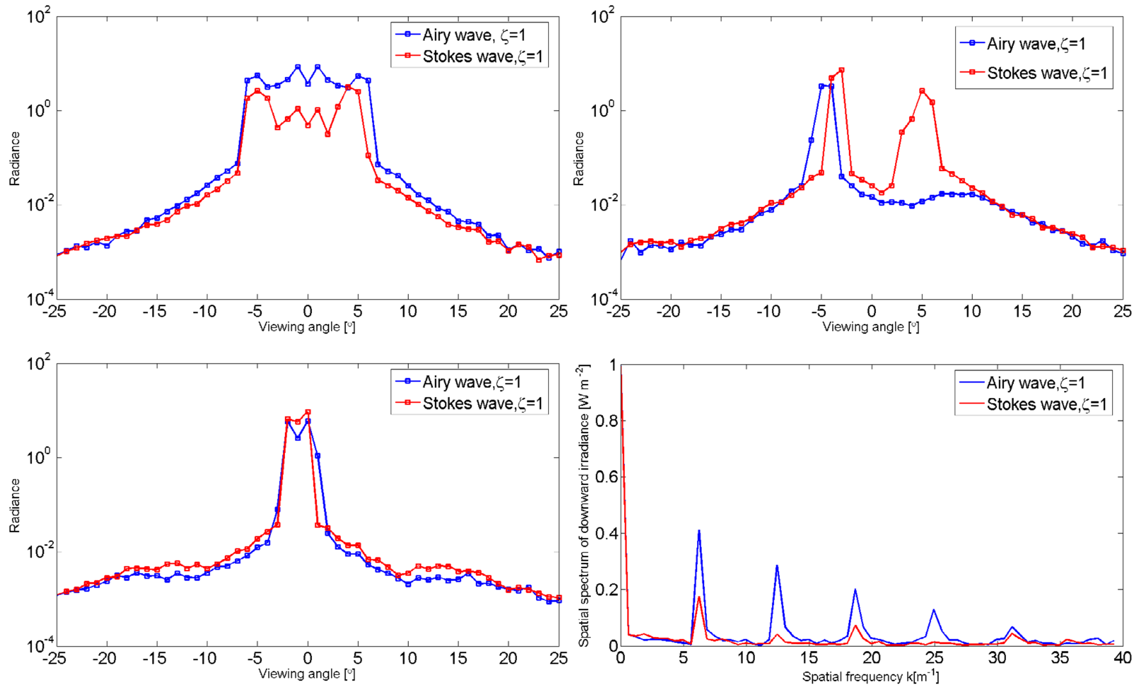


Figure 2. Comparison of radiance distribution at optical depth ζ=1 under an Airy wave (blue line) and a fully nonlinear Stokes wave (red line). The plotted are the results for the receiver point below the crest (top left), 90^o phase point (top right), and the trough (bottom left). The bottom right picture shows the spatial spectrum of downwelling irradiance at ζ=1.

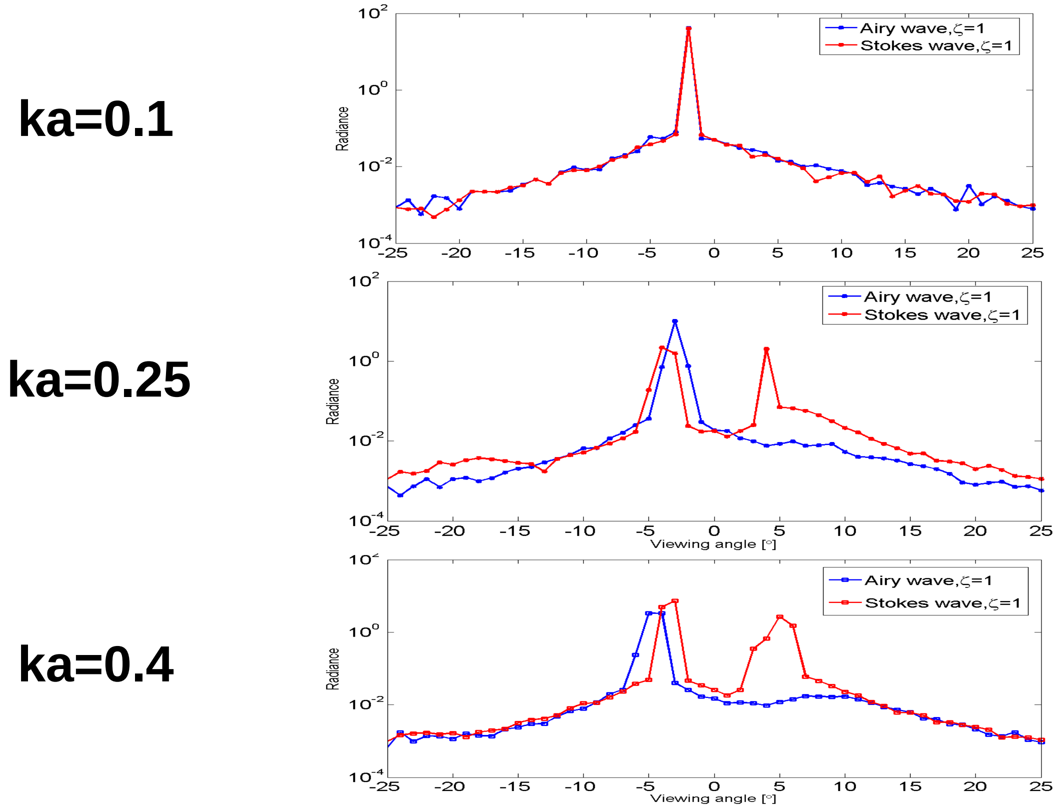
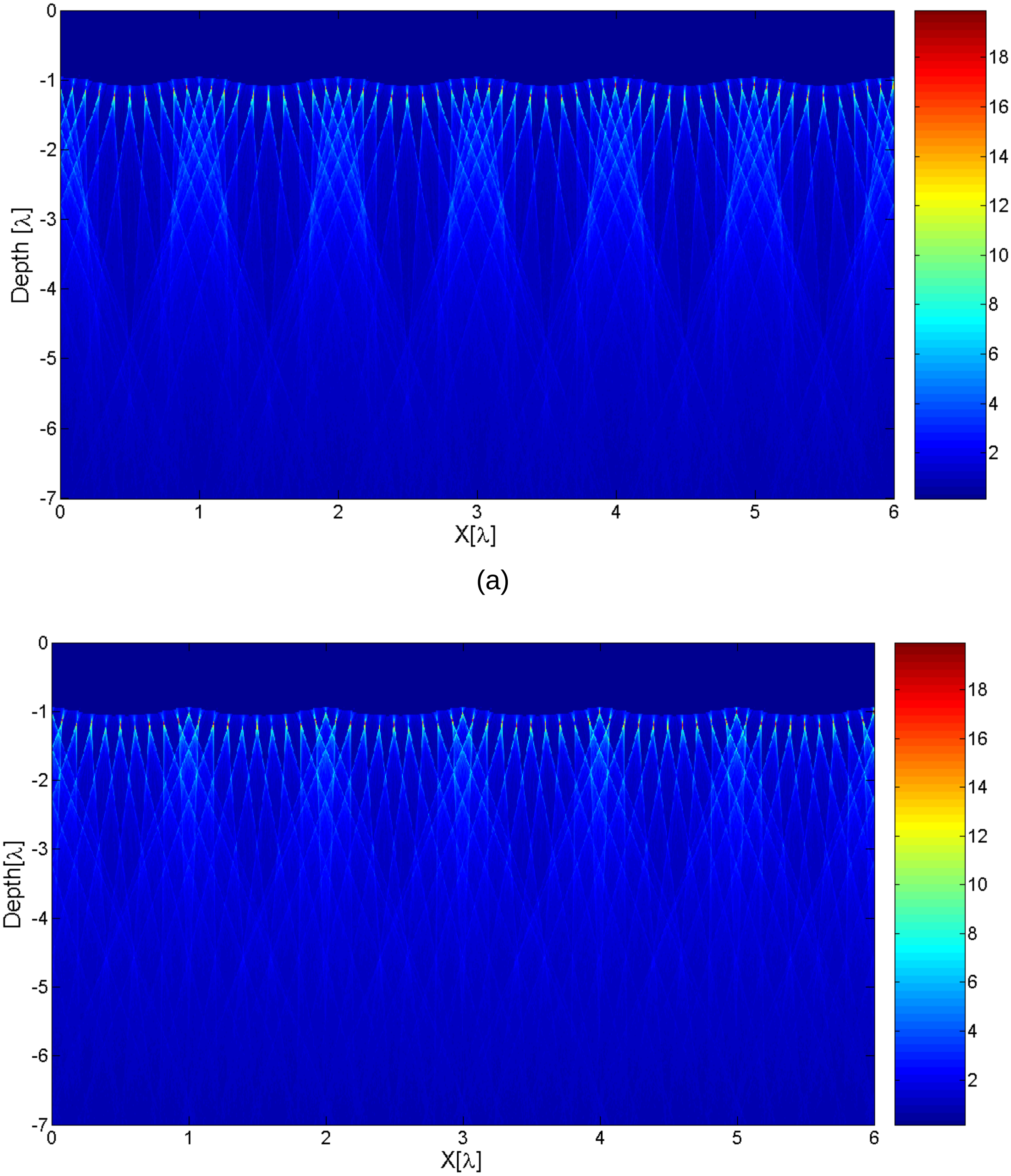


Figure 3. Comparison of radiance distribution at optical depth ζ=1 under the 90^{o} phase point in Airy wave (blue line) and a fully nonlinear Stokes wave (red line) with the wave steepness ka = 0.1 (top figure), ka = 0.25 (middle figure), and ka = 0.4 (bottom figure).



(a)

(b)

Figure 4. Downwelling irradiance pattern under (a) linear Airy and (b) nonlinear Stokes waves in the presence of short waves.